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Photons and Particle Production in Cassiopeia A: Predictions from Nonlinear Diffusive Shock Acceleration

Donald C. Ellison[1], Philippe Goret[2], Matthew G. Baring[3]
Isabelle A. Grenier[2] and Pierre-Olivier Lagage[2]
[1]*Physics Department, North Carolina State University, Raleigh, NC 27695-8202, USA*
[2]*Service d'Astrophysique, CEA, DAPNIA, Centre d'Etudes de Saclay, 91191 Gif-sur-Yvette, France*
[3]*Universities Space Research Association, LHEA, NASA/GSFC, Greenbelt, MD 20771, USA*

Abstract

We calculate particle spectra and continuum photon emission from the Cassiopeia A supernova remnant (SNR). The particle spectra, ion and electron, result from diffusive shock acceleration at the forward SNR shock and are determined with a nonlinear Monte Carlo calculation. The calculation self-consistently determines the shock structure under the influence of ion pressure, and includes a simple parameterized treatment of electron injection and acceleration. Our results are compared to photon observations, concentrating on the connection between the Radio and GeV–TeV gamma-ray range, and to cosmic ray ion observations. We include new upper limits from the Cherenkov Array at Thémis (CAT) imaging Cherenkov telescope and the Whipple 10m γ-ray telescope at > 400 GeV. These new limits support the suggestion (e.g., Cowsik & Sarkar 1980; Allen et al. 1997) that energetic electrons are emitting synchrotron radiation in an extremely high magnetic field ($\sim 1000\mu$G), far greater than values routinely assigned to the ISM, and help to constrain our model. The large magnetic field allows acceleration of cosmic ray ions to well above 10^{15} eV per nucleon in the ~ 300 yr lifetime of Cas A.

1 Introduction

We describe particle acceleration in an expanding, spherical SNR blast wave with a plane-wave, steady-state shock model. The justification for using a steady-state calculation to model time-dependent SNRs is given in Ellison & Berezhko (1999) and the full details and assumptions of our model are given in Baring et al. (1999). Briefly, the global SNR shock parameters (e.g., shock speed and radius as a function of remnant age) used as input for the model, are estimated with a simple Sedov solution of the evolving blast wave in an uniform medium. Given the global shock dynamics, we are able to calculate the shock structure and first-order particle acceleration assuming that electrons and ions are accelerated directly by the forward shock, leaving considerations of the reverse shock, where substantial X-ray emission may originate, for later work. Important limitations of our current model is that we do not consider oblique magnetic field structures or include second-order Fermi acceleration, which may be important in the low Alfvén Mach number shocks ($M_{A1} \sim 4$ for the parameters we show here) implied by the large B-fields (see Bykov & Uvarov 1999 for a model of electron injection which does include 2nd-order acceleration).

For the particular case of Cas A, the forward shock may be interacting with pre-supernova wind material swept into a relatively dense shell (e.g., Borkowski et al. 1996) which may account for the high magnetic field if the stellar magnetic field was compressed along with the wind material. Alternatively, the large field may be the result of amplification by turbulent eddies (Keohane 1998 and references therein). If magnetic fields $B \sim 1000\mu$G dominate the acceleration region, ions can be accelerated to well above 10^{15} eV/nuc. While the overall fluxes of these particles may not be sufficient to provide the bulk of the cosmic rays at 1-10 GeV because of the small numbers of particles swept up, particle spectra from young SNRs might be harder than from older, slower SNRs and may dominate above $\sim 10^{14}$ eV through the 'knee' near 10^{15} eV.

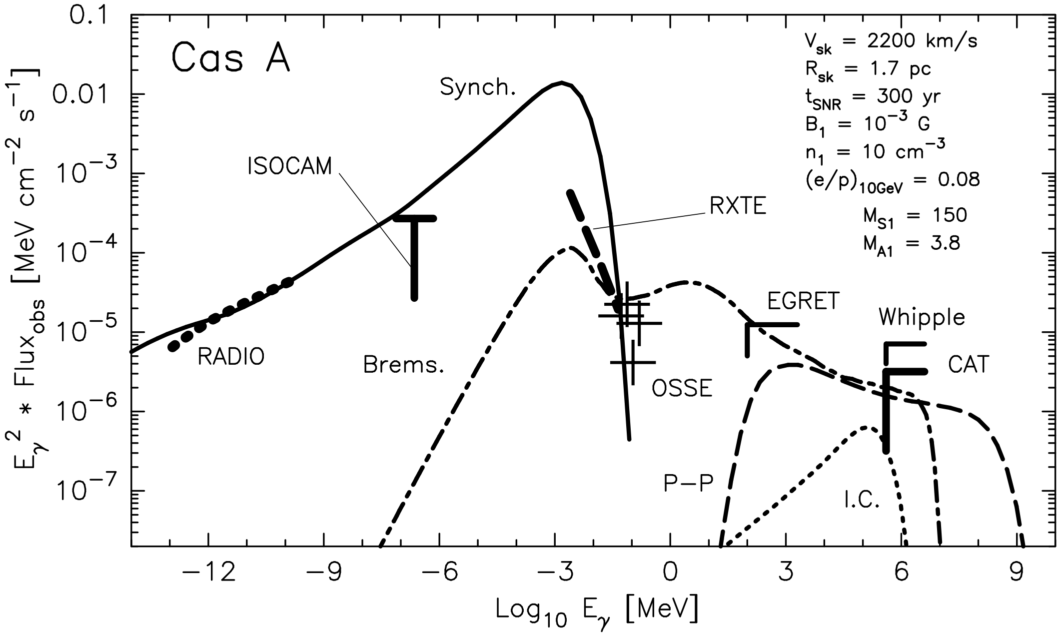

Figure 1: *Cassiopeia A spectrum. Observations are from Baars et al. (1977: radio); Lagage et al. (1999, in preparation: ISOCAM); The et al. (1996: RXTE and OSSE); Esposito et al. (1996: EGRET); Lessard et al. (1999: Whipple); and Goret et al. (1999: CAT). The model photons come from a single set of proton, helium, and electron spectra calculated with unshocked parameters shown in the figure. A single normalization has been applied to all components to match the radio flux. The subscript '1' indicates unshocked values and M_{S1} and M_{A1} are the sonic and Alfvén Mach numbers. Note that the bremsstrahlung emission cuts off at a much lower energy than the pion-decay due to the synchrotron losses the electrons experience. In these preliminary results, the inverse Compton does not included synchrotron-self-Compton although this may dominate the inverse Compton from the primordial background radiation.*

Not only does the high B-field make it possible to produce cosmic rays to $> 10^{15}$ eV, but a homogeneous model with a single set of parameters can be found which affords a reasonable fit to the *intensities* of diffuse photon emission from radio to γ-rays. Limits imposed by the radio and γ-ray observations allow us to place constrains on the electron-to-proton ratios produced by shock acceleration. The detailed *shapes* of individual components (e.g., radio, X-ray), however, are difficult to model with a single set of parameters. Despite this limitation, important model and/or environmental constraints can be inferred if it is assumed that the relativistic electrons responsible for the radio synchrotron emission also produce the diffuse infrared and X-ray continuum via the synchrotron mechanism, (and in the same emitting volume). Likewise, if the GeV and TeV γ-ray emission is dominated by inverse Compton and bremsstrahlung emission (rather than pion-decay from energetic ions), it can be assumed that these same relativistic electrons are responsible for the GeV and TeV gamma rays. Assuming a homogeneous environment precludes, of course, the modeling of emission from the lumpy morphology, knots, ring structure, etc., that characterizes high spatial resolution observations of Cas A.

2 Results

In Fig. 1 we compare our results to observations of Cas A from radio to TeV γ-rays. We have a single normalization for all of the model components and this has been chosen to match the radio flux. Since the same electron distribution that produces the radio emission can also produce bremsstrahlung

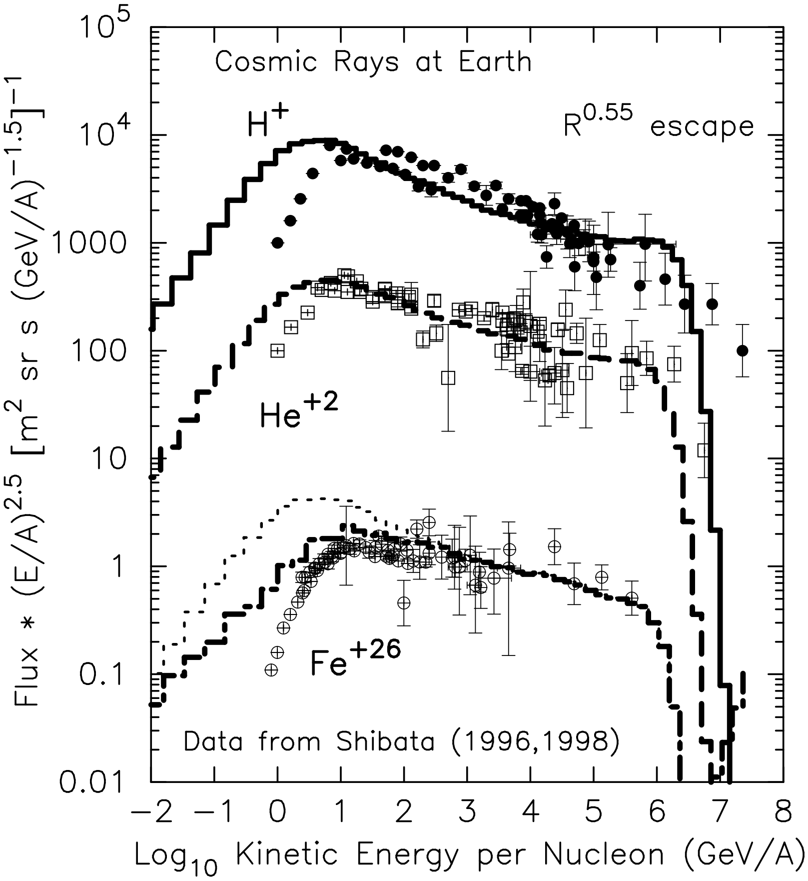

Figure 2: *Cosmic ray spectra measured at the Earth (data from Shibata 1996, 1998) compared to model spectra with same parameters as shown in Fig. 1. The model spectra have been multiplied by Rigidity*$^{-0.55}$ *to account for escape during propagation and have been normalized separately to match the observations. The light dotted histogram is the model Fe spectrum without nuclear destruction during propagation while the dot-dashed histogram includes nuclear destruction. The turnover in the data below* ~ 1 *GeV/A is from solar modulation, which is not included in the model.*

and inverse Compton emission at GeV-TeV energies, the combination of the observed radio intensity and the low γ-ray upper limits forces the conclusion that the magnetic field is exceedingly high. Otherwise, the bremsstrahlung and inverse Compton emission at TeV energies would have been observed. This might not be the case if the radio emitting electrons occupy a greater emission volume than GeV-TeV emitting electrons, or that the lower energy (i.e., radio-emitting) electrons can preferentially sample regions of clumped magnetic field and/or density. Even if either of these cases arises, the inverse Compton component, which depends at most only weakly on the background particle density, will set a lower limit on B that remains well above standard ISM values. Note that the cosmic microwave background radiation forms the seed for inverse Compton scattering in the present exposition; work is in progress to include synchrotron self-Compton contributions, which will tighten the constraints discussed here, implying even higher B-fields.

The relative importance of the pion-decay emission depends sensitively on the model parameters and we have not yet done a careful survey of the parameter space. For our preliminary results shown in Fig. 1, we have chosen our electron injection parameters to give an electron to proton ratio at relativistic energies, $(e/p)_{10\mathrm{GeV}} \simeq 0.08$, somewhat above observed cosmic ray values.

We again emphasize that even though our model is for plane-parallel, steady-state shocks, de-

tailed comparisons (Ellison & Berezhko 1999) with the spherically symmetric, time-dependent model of Berezhko (1996; see also Berezhko, et al. 1996) show that the steady-state and plane shock approximations do not seriously influence the results as long as the diffusion length of the highest energy particles is a small fraction of the shock radius, $R_{\rm sk}$, as should be the case in Cas A and other young SNRs. If Cas A is currently interacting with a relatively dense shell of material formed from the pre-SN wind (Borkowski et al. 1996), the Sedov solution can be replaced by estimates of the ambient density, n_1, magnetic field, B_1, $R_{\rm sk}$, and $V_{\rm sk}$, which translate to maximum particle energies.

3 Conclusions

The observed radio intensity of Cas A, combined with the EGRET and TeV upper limits, imply magnetic fields $\gtrsim 1000\mu$G. Fields this large make it possible to accelerate cosmic ray ions to above 10^{15} eV/nuc in the $\sim 300\,$yr lifetime of the remnant, since the time to shock accelerate ions of charge Q to $E_{\rm max}$ is (e.g., Baring et al. 1999)

$$t_{\rm acc} \simeq 190 \left(\frac{\eta}{Q}\right) \left(\frac{V_{\rm sk}}{2000\,{\rm km/s}}\right)^{-2} \left(\frac{B}{10^{-3}\,{\rm G}}\right)^{-1} \left(\frac{E_{\rm max}}{10^{15}\,{\rm eV}}\right) {\rm yr}\ .$$

Here, η is the number of gyroradii in a scattering mean free path and is approximately one in the Bohm limit, which we assume in this model. In Fig. 2 we compare the model spectra, all multiplied by $R^{-0.55}$ [$R = pc/(Qe)$] to model rigidity-dependent escape during propagation, with cosmic ray observations. No attempt has been made to model the *abundances* of these components, each being separately normalized to match the observations. It's clear that the spectra extend through the knee region. Young SNR shocks sweep up far less ISM material than older, larger shocks, but the high energy cosmic rays produced may have flatter spectra than the bulk of the cosmic rays accelerated by older SNRs which have weaker shocks and, if so, could dominate the cosmic ray flux near the knee. If this is the case, spectral (and perhaps compositional) features should exist in the cosmic ray spectra as these components become dominant.

If high B-fields are common in young SNRs, it has important implications for γ-ray emissivity as well as cosmic ray production. High fields imply that radio intensities will be high, concomitant with relatively low relativistic electron fluxes (and presumably low relativistic ion fluxes as well), lowering the γ-ray emissivity. Therefore, radio loud SNRs may not be the best candidates for γ-ray studies, and some other indicator may be required to guide observational programs.

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